Summary of the RIA Applications Workshop

October 30-31, 2000
Los Alamos National Laboratory

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I. Executive Summary

Approximately 55 people attended this two-day workshop on the applied uses of the proposed Rare Isotope Accelerator (RIA). Applications were explored by four separate working groups. The findings of each working group are summarized below.

Radioisotope Production and Biomedical Research
With RIA's very high beam intensity and its mass and fragment separation capabilities, there is a significant opportunity to produce a wide variety of radioisotopes of interest to the biomedical research community and others. It is possible to peel off a small portion of the primary beam at the first stripper and use (HI,xn) reactions to produce a variety of neutron-deficient isotopes in high purities which are not currently available, such as the alpha emitter ^{149}Tb produced via the ^{141}Pr(^{12}C,4n) reaction. The ability to collect extraordinarily high specific activities of long-lived species using the fragment separator and/or the mass separator was also highlighted as being important. In particular, at a separated radioactive beam intensity of 10^{11}/s, this corresponds to a collection rate of ~10^{16} atoms/day or ~3 μg/day at A=200. The availability of such high-purity (mass-separated) radioisotopes will greatly advance future research in the development of radiomedical diagnostics and radiotherapy. Finally the ability to post-accelerate radioactive species and implant them into various substrates (such as seeds and stints) is well suited to evolving radiotherapy applications.

Nuclear Physics Needs for Science-Based Stockpile Stewardship (SBSS)
SBSS is aimed at certifying and maintaining the nation's aging nuclear stockpile. Achieving this goal in part involves obtaining an improved understanding of the nuclear physics, where much of the uncertainty lies in our knowledge of nuclear reactions off the line of stability. RIA will provide the capability to measure important reaction cross sections and to improve models that calculate them. The use of inverse kinematic reactions using radioactive beams, such as ^{8}Li(p,t) and ^{239}U(d,pf) to simulate (n,f) reactions, represent a powerful tool with which to measure these cross sections. For long-lived species ($t_{1/2}$ > 1-5 day), it is possible to collect pure mass-separated samples in target quantities that could then be taken to a high-intensity neutron facility for the measurement of neutron-induced reactions, such as (n,γ), (n,xn), or (n,f). These are extremely important measurements for the SBSS program. Finally, interest was expressed in the onsite production of neutrons at RIA using either the primary beam or from a separate neutron generator co-located at RIA to carry out neutron-induced reaction measurements on short-lived radionuclides and isomeric species.

R&D Related to Accelerator Transmutation of Waste (ATW)

ATW technology aims to transmute, through fast (10 keV - 20 MeV) neutron-induced fission and radiative capture reactions, long-lived radioactive species into shorter-lived species with half-lives typically less than 300 years. RIA could be used to collect pure mass-separated samples of selected actinide and fission product species and produce radioactive targets for the measurement of the important fission and capture cross sections at a neutron facility. Fission probabilities could also be measured in inverse kinematics (d,pf) or similar stripping reactions which mimic (n,f) reactions (at least at neutron equivalent energies above ~0.5 MeV). Other studies, such as those recently performed at GSI, involving the measurement of spallation and fission product distributions following A+p inverse kinematic reactions have been instrumental in testing and improving intranuclear cascade and pre-equilibrium models used in ATW calculations. Additional measurements of this type would be extremely valuable in further improving these models.

Materials Science and Other Applications

The use of radioactive tracers implanted into materials is a developing and potentially powerful tool for the field of materials science and surface physics. In particular, radioactive beam implantation for wear and corrosion studies, beta-NMR studies of high T_c superconductors, semiconductors, magnetism, and perturbed angular correlation studies of materials are important potential applications. At RIA intensities, material modification studies using doping and annealing techniques could also be done. Other areas of interest include space radiation effect studies with stable and radioactive beams, radioactive beam implantation for medical radiotherapy (see the biomedical applications section), neutron cross sections, neutron damage, and radiation effect studies with high-energy (20-400 MeV) neutrons produced as well as projectile fragmentation and the possibility of slowing these neutrons down to ultra-cold temperatures. The commercial use of radioactive beams appeared to be a limited, but viable option.

Facility Implications for Applied Research at RIA

Although some of the applied research discussed here would utilize the primary post-accelerated, high-intensity RIA beam, many experiments could be run as a secondary (or parasitic) user. In particular, flexibility should be built into RIA to utilize multiple targets, beam switching/sharing, and broad-range mass separation or pre-separation/post-separation fragment separator ideas to feed multiple users. Although the community was concerned about facility creep, many of these ideas are relatively simple and cost efficient if implemented up front. If sufficient room and flexibility is designed into the target and initial mass separation/recoil selection regions, other more involved ideas could be implemented as future enhancements. Increasing beam usage and flexibility is the key.

Two major recommendations from this community are: (1) including the capability to collect mass-separated/recoil-separated radioactive samples for the production of long-lived ($t_{1/2}$ > 2-5 day) radioactive targets and (2) building a high-intensity area to utilize the stable beam of the primary accelerator for radioisotope production via (HI,xn) reactions and for stable beam + radioactive target experiments. Additional RF power maybe required in the early stable beam acceleration stages to fully utilize this latter capability.

II. Radioisotope Production and Biomedical Research at RIA

Conveners: Jose Alonso (LBNL) and Dennis Phillips (LANL)

Working Group Participants:
Jose Alonso (LBNL), Robert Atcher (LANL), David Jamriska (LANL), Jerry Nolen (ANL), Meiring Nortier (NAC), Maria Petra (ANL), Dennis Phillips (LANL), Mauricio Portillo (ANL), Werner Richter (U. of Stellenbosch), Thomas Ruth (TRIUMF)

Abstract:

With RIA's very high beam intensity and its mass and fragment separation capabilities, there is a great opportunity to produce a wide variety of radioisotopes of interest to the biomedical research community and others. Interest was expressed in (HI,xn) reactions using a small portion of the primary beam pealed off after the first stripper to produce a variety of neutron-deficient isotopes in high purities which are not currently available, such as the alpha emitter ^{149}Tb produced via the ^{141}Pr(^{12}C,4n) reaction. The ability to collect extraordinarily high specific activities of long-lived species using the fragment separator and/or the mass separator was also highlighted as being important. In particular, at a separated radioactive beam intensity of 10^{11}/s, this corresponds to a collection rate of ~10^{16} atoms/day or ~3 μg/day at A=200. The availability of such high-purity (mass-separated) radioisotopes would greatly advance future research in the development of radiomedical diagnostics and radiotherapy. Finally the ability to post-accelerate radioactive species and implant them into various substrates (such as seeds and stints) is well suited to evolving radiotherapy applications.

Highlight - Two Interesting Possibilities:

a. Using a variety of reaction mechanisms, RIA could be used to produce a portfolio of isotopes in amounts useful in a variety of research applications (10^{10} – 10^{20} atoms). Some of these nuclides are not accessible by accelerator facilities currently producing isotopes. The facility could yield nuclides in unprecedented high specific activity approaching the theoretical maximum.
b. The accelerator could be used to implant radioactive materials in various substrates that could yield devices uniquely suited to radiotherapy.

Introduction

RIA presents unique opportunities for production of radionuclides for research in various aspects of medicine and science. The facility can provide multiple locations for construction of target irradiation facilities along the driver linac. Compound nucleus reactions, (particle, xn), and spallation processes could yield practical quantities (10^{10}-10^{20} atoms) of specific nuclides.

The capability of RIA to produce separated radioactive beams at rates approaching 10^{10} atoms/sec presents the prospect of recovering research quantities of very high specific activity nuclides. These isotopes would be useful for tracer research and for isotope dilution mass spectrometry. Biodistribution studies using high-purity products with near theoretical specific activity would provide unique data for evaluating the potential medical utility of certain nuclides.

Producing fragments by acceleration of high-mass ions onto a low-mass target allows access to nuclides that cannot presently be produced. The high-specific-activity fragment nuclide from the separated beam could be collected. The unseparated fragments might be recovered from a beam dump behind the fragmentation target.

The availability of relatively high-intensity beam of high-energy neutrons creates the prospect of producing neutron-rich nuclides not normally accessible by simple neutron reactions. Another potential biomedical application of RIA might include research into production of brachytherapy sources by ion implantation. The facility could potentially accommodate heavy-ion particle beam therapy if it were configured to allow true multi-user capability.

RIA Assets

The multiplicity of possible ports, beams, production mechanisms and energies all contribute to the ways that RIA could contribute uniquely to radioisotope production. Several, but not all, of these opportunities come about in a totally non-interfering mode, by using beam not part of mainstream activities (charge-states not accepted for further acceleration, beam dumps, secondary spectrometer channels, etc.). Each will be discussed in turn.

1. Stripper I

Starting with the lowest energies, at the first stripper location, where beam energies are close to the Coulomb barrier, compound-nucleus reactions can be used to produce a wide range of isotopes with high purity. The excitation functions for (HI, xn) reactions are very clean, with high cross sections; and the kinematics of recoiling product nuclei can be used to facilitate separation and purification. Being able to choose a range of ion beams increases options for selection of target material that have suitable properties of isotope fraction (preferably monoisotopic) and physical characteristics (ability to withstand high beam power), that offer attractive possibilities for economic production capabilities. Isotopes produced would be on the neutron-deficient side, many of which are not currently available to the medical community, but which might offer very attractive properties for therapeutic or diagnostic applications.

RIA could serve as a demonstration platform, possibly also producing batches of isotopes on a limited scale, but sufficient to conduct research activities necessary for establishing medical viability of particular isotopes. The technology associated with the RIA Driver could be replicated for dedicated isotope-production facilities once clinical and economic viability has been established.

While production efficiencies and yields can be demonstrated at any heavy ion accelerator capable of beams at energies around the Coulomb barrier; RIA would be required to produce the levels of activity needed for research programs, and also for the engineering developments of target systems capable of supporting the heat-loads associated with the necessary bombardment conditions.

2. Stripper II

A second irradiation station could be provided at the second stripper (180° bend) where beam energies are around 100 MeV/u. Capable of producing exotic nuclei via more complex reaction mechanisms, e.g. spallation, the flexibility of beam and target species can provide a wide range of possibilities. Yields would not be as high, because of the wide diversity of reaction channels, but useful quantities of isotopes could still be separated, and the station could be used with beam not acceptable for further acceleration as a parasitic user.

3. ISOL Target area

The extremely high fluxes of light-ions (mainly protons) and neutrons around the ISOL target can be utilized for isotope production, either by bombardment of specific target material placed in areas of suitable flux, or by processing of waste target materials. As such irradiations would most likely occur in batch mode, isotopes most likely to result would be long-lived, exotic products of use for environmental or geological research.

4. Fragmentation target

Numerous opportunities are available from the fragmentation target. A heavy beam, such as uranium, is passed through a thin liquid lithium target, in which a fraction of the primary beam undergoes reactions. Downstream spectrometers analyze the products, separating generally a single species for further analysis and post-acceleration.

a. Secondary channels

Spectrometers will be tuned to accept a single isotope, while all the other isotopes produced will be rejected from the primary channel. By suitable design, these other isotopes can be collected at different stations, and then used for ancillary research. In all likelihood, isotopes so collected will not be of high purity, and may require subsequent chemical or spectroscopic separation.

b. Primary channel

By utilizing the primary channel, very high purity isotopes can be collected. While making use of the principal experimental resources, very high-priority programs could make use of these capabilities for research applications.

c. Neutron flux

The uranium beam at 400 MeV/u in reacting in the lithium target produces an intense flux of neutrons traveling with the beam velocity. The strong kinematic focusing allows for a high-density beam of mono-energetic neutrons at a suitable distance (10's to 100's of meters) from the target, to enable reactions with these high-energy neutrons to be studied in a very clean, low-background environment.

d. Backstops

Only a small fraction of the uranium beam passing through the fragmentation target undergoes interactions; the remaining beam is transported to a beam dump or stop. The opportunity exists for selecting material for this dump to enable subsidiary reactions. Beam-stop areas can be designed for rapid, even continuous cycling of catchers for routine production capabilities.

Ancillary facilities:

It should be noted that RIA would have support facilities for handling high-level activity that can be utilized very effectively for radiochemical separation and handling of isotopic products. These facilities will be of extreme value for these programs and should not place an undue burden on the mainstream use of these resources.

Important consideration:

Note that many of these programs, particularly isotope production at the Stripper I area, are made much more attractive by having flexible, multi-beam capabilities in RIA. If the isotope-production programs can be operated with little or no interference with ongoing primary experiments, significant enhancements in availability and overall productivity can result. The RIA machine designers are strongly urged to build this type of flexibility into the machine designs!

Isotope Production at RIA

Recognizing that the future growth of Nuclear Medicine will be in the development of radiotoxic materials to be used in therapy, the unique facilities at RIA will enable researchers to explore a wide range of radioisotopes that possess the physical and chemical properties for the appropriate therapeutic use. The choice of radioisotope can be tailored to reflect half-life, decay mode, and chemical reactivity. The ability to perform compound nucleus reactions with heavy ions will open channels to radioisotopes at purities not achievable anywhere else. For example, the production of the alpha-emitter ^{149}Tb via the ^{141}Pr(^{12}C,4n) reaction would be possible.

In addition the precursor to the alpha-emitting isotopes ^{211}At would be possible by irradiating a bismuth target with a lithium ion beam to induce the ^{209}Bi(^{7}Li,5n)^{211}Rn reaction. While the cross section for this reaction has been reported, the practical issues of handling ^{211}Rn for optimizing the chemistry with ^{211}At has yet to be explored. RIA would allow sufficient quantities of ^{211}Rn to be produced to carry out chemical experiments in addition to the advantage of having a precursor (^{211}Rn) with a half-life that extends the shelf life of this important alpha-emitter.

The ability to utilize the fragmentation of heavy nuclides such as ^{238}U at 400 MeV/u provides exciting opportunities to access radioisotopes of extraordinarily high specific activity. Characterizing the biochemical behavior of radioisotopes at theoretical specific activities may enable radiation biologists to explore cell death under radiation conditions not previously available. The ability to explore the impact on biodistribution with these ultra-pure materials could provide guideposts as to where future research in the development of radiotherapy with isotopes should go.

Having accelerated radioactive species with kinetic energies from a few keV to hundreds of MeV/u would enable research into implantation of radionuclides into various substrates. The resulting materials could be used in novel ways to support brachytherapy, and important application of radionuclides in medicine. One can imagine the implantation of isotopes into seeds or stints in a unique pattern to achieve the dose profile to fit the biological application at hand. The implantation work would allow "proof of principle" research to be performed that could open opportunities for the private sector to pursue at a practical level.

RIA could be used to produce numerous long-lived isotopes at very high specific activity of research interest to the environmental, geochemical, and medical communities. Production by fragmentation reactions followed by mass separation could, for example, produce research quantities of separated ^{92}Nb, ^{60}Fe, and ^{53}Mn for mass spectrometric work. The geochemical community has expressed interest in obtaining separated ^{97}Tc and ^{98}Tc as tracers of ^{99}Tc in the environment. Researchers in the earth and space sciences have expressed interest in obtaining heavy nuclides such as ^{205}Pb. Biomedical researchers studying berylliosis have requested tracer quantities of ^{10}Be for AMS research. If RIA could provide quantities of these isotopes in the range of 10^{13} to 10^{15} atoms, these applications could be realized.

RIA and Particle Beam Therapy

The general consensus is that the use of RIA for research into particle beam therapy would not be compatible with the science mission of the facility. The use of the facility for beam therapy could not be accommodated parasitically (invisibly) to the beam experiments for nuclear science. Beam time would probably have to be allotted to a particle beam therapy facility at the expense of other applications. However, if a true multi-use capability could be sufficiently developed allowing sharing of beam time, it would be possible to take advantage of the great variety of projectiles offered for experimental radiotherapy. For example beams such as ^{12}C provide an opportunity to treat certain types of tumors effectively. Currently there are only two heavy-ion therapy facilities in operation in the world (Japan and Germany). A few new heavy ion facilities are likely to be built but these are very expensive and the number will be limited. RIA might be used to provide the convincing evidence that heavy ions are a better treatment modality than protons to encourage the construction of full-scale treatment facilities.

Working group speakers and discussion titles:

Jose Alonso (LBNL), "Radioisotope and Biomedical Applications of RIA" (plenary talk)
Dennis Phillips (LANL), "Introductory Remarks"
Jerry Nolen (ANL), "Overview of Possibilities for Medical and Industrial Isotope Production at RIA"
Thoms Ruth (TRIUMF), "Radioisotopes for Biosciences"
Robert Atcher (LANL), Heavy Nuclides for Nuclear Medicine"
Meiring Nortier (NAC) and Werner Richter (U. of Stellenbosch), "Medical Applications of the South African National Accelerator Centre (NAC): Radioisotope Production and Particle Beam Therapy"

III. Nuclear Physics for Science Based Stockpile Stewardship at RIA

Conveners: Anna Hayes (LANL) and Lee Bernstein (LLNL)

Working group participants:
Stephanie Frankle, Robert Little, Johndale Solem, Mike MacInnes, Jerry Wilhelmy, Thurman Talley, Gerry Hale, Robert Haight, Anna Hayes, John Ullmann, Steve Wender, Darrell Drake, Stephen Becker, Matthew Devlin, Lee Bernstein, Dennis Slaughter, Mark Stoyer, Andre Michaudon, Ben Gibson, and Ron Nelson

Abstract:

The Science-Based Stockpile Stewardship (SBSS) program is aimed at certifying and maintaining the nation's aging nuclear stockpile. Achieving this goal in part involves obtaining an improved understanding of the nuclear physics, where much of the uncertainty lies in our knowledge of nuclear reactions off the line of stability. RIA will provide an opportunity to measure important reaction cross sections and to improve models that calculate them. The use of inverse kinematic reactions using radioactive beams, such as ^{8}Li(p,t) and ^{239}U(d,pf) to simulate (n,f) reactions, represent a powerful tool with which to measure these cross sections. For long-lived species ($t_{1/2}$ > 1-5 day), the ability to collect pure mass-separated samples in target quantities that could then be taken to a high-intensity neutron facility for the measurement of neutron-induced reactions, such as (n,γ), (n,xn), or (n,f), received considerable attention. Finally, there was interest expressed in the onsite production of neutrons at RIA or the possibility of having a separate neutron generator co-located at RIA to carry out neutron-induced reaction measurements on short-lived radionuclides and isomeric species.

Highlight - two interesting possibilities:

a. Thermonuclear reactions involving unstable ions
   Radioactive ions such as ^{6}He, ^{7}Be, and ^{8}Li are produced in thermonuclear environments. The cross sections for both producing and destroying these nuclides through interactions with the stable isotopes of H, He and Li are an important need. RIA will provide intense beams of these unstable ions over the entire energy range of interest for SBSS.

b. Bucket collection mass-separated (or recoil separated) radioactive species in parasitic mode
   A significant number of the isotopes of interest to the SBSS program have half-lives of the order of days or longer. By producing these isotopes in target quantities at RIA and then transporting the targets to a high-intensity neutron facility, such as LANSCE, one could measure the important neutron reactions of interest. We envision a collection rate of tens of micro-grams of mass-separated or recoil separated, long-lived isotopes in a parasitic "bucket collection" mode.

Detailed Summary Of The SBSS RIA Sessions

The main goal of the Science Based Stockpile Steward Program (SBSS) is to understand the effect of aging on the nation's weapons stockpile. This requires a detailed scientific understanding of device performance, including the nuclear physics issues involved. Both the very high neutron fluence and the thermonuclear environment involved in nuclear explosions produce a number of radioactive nuclei, and there is a clear need in the SBSS Program for cross section information on these radioactive species. This workshop explored the possibilities of addressing some of these key issues at a RIA facility and several specific areas of interest were identified.

The nuclear physics needs of the SBSS program fall into four main areas: (1) light-ion thermonuclear reaction rates; (2) neutron and light charged-particle cross section on mid-mass radioactive isotopes and isomers; (3) cross sections for and properties of fission products; and (4) neutron reactions on both short-lived and long-lived unstable actinides.

The needs for the thermonuclear program mainly lie in the reactions of ^{8}Li, ^{6}He and ^{7}Be with the stable isotopes of H, He and Li. Although some of the production cross sections have been measured, in the few cases for which multiple data sets exist they are usually discrepant. In addition to the production cross sections, cross sections and angular distributions for the destruction of radioactive light ions by the same stable isotopes are also of interest. A useful specific case is that of a ^{8}Li beam impinging on a ^{1}H target. This investigation would take advantage of inverse kinematics to concentrate the reaction products forward in a narrow forward angle “focused” cone in the laboratory system. By detecting the outgoing deuterons and tritons from the reaction (tritons would occur only for beam energies above 7.2 MeV), two of the primary production reactions for ^{8}Li could be measured in the reverse direction. An accurate determination of the absolute normalization of these measurements would be required since present measurements for ^{7}Li(d,p)^{8}Li disagree by as much as 50%. The desired range of beam energies would be from as low as possible (~0.1 MeV/u) up to ~20 MeV/u. The lower end of this range (<5 MeV/u) may be covered by the Notre Dame accelerator or Oak Ridge HRIB facility. However, there is no existing US facility that covers the energy range up to 20 MeV/u. (MSU has recently upgraded to the coupled cyclotron producing beams typically around 200 MeV/u. It is unlikely that beams as low as 20 MeV/u would be produced by this facility.) The only possibility for covering the entire range with a single, high-intensity beam (thus avoiding the problem of multiple normalizations) is the proposed RIA facility.

The three major actinide fission fuels all produce about 100 fragment/product masses with about 3 to 5 isobars for each mass. Clearly, some selectivity is required to construct a tractable measurement program pointing to substantiative progress. However, RIA could play an important role here by supporting a theoretical program to determine the average properties of these. In addition to providing measurements of the cross sections on a few selected fission products, measurements at RIA could provide more detailed knowledge of both discrete and continuum nuclear level densities and of the optical potentials needed for their theoretical evaluations.

In nuclear tests, neutron fluences were monitored using so-called radiochemical tracers. The high neutron fluences involved in nuclear explosions insured that an entire chain of isotopes of the tracer was formed, in an exactly analogous manner to isotope chain production in explosive stellar environments. Most of the unstable isotopes of interest to the SBSS program have lifetimes of the order of days or more, and RIA could produce these isotopes in sufficient quantity for target manufacture, with subsequent cross section measurements carried out at another facility. The RIA high-intensity beams of nuclear species off the line of stability will allow the production of radioactive targets of interest in parasitic “bucket collection” mode. By taking advantage of the high-efficiency, high-resolution, 4π-barium fluoride gamma detector DANCE array being constructed at LANSCE, for example, accurate measurements of the neutron capture cross sections will be possible on radioactive targets consisting of just tens of micro-grams. A long list of isotopes of interest for radiochemical analyses exists, including the unstable isotopes of Tm, Ir, Y, Lu, Zr and Bi. The most important reactions of interest are the neutron capture cross sections and the (n,2n) cross sections in the neutron energy range (0-20 MeV). Additionally, light charged-particle reactions on radiochemical tracer isotopes are of interest to the program. To give a specific example, the present calculations for the capture cross section ^{168}Tm(n,γ) in the 0-100 keV range differ by an order of magnitude. A measurement of this cross section to an accuracy of 30-50% would provide an important constraint for the radiochemical tracer analyses.

In addition to producing mass-separated radioactive targets of tracer isotopes, “bucket collection” techniques could provide targets of the important unstable actinides such as ^{237}U (6.7 days) plus several Pa and Th isotopes. On such targets, fission and other neutron-induced reaction measurements are quite feasible. However, there is also an interest in short-lived unstable actinides, such as $^{239-240}$U, as well as short-lived isomers and isotopes for which measurement would clearly have to take place at RIA. For the fission cross sections, inverse kinematics using the (d,pf) reaction is a clear possibility. However, the importance of neutron-induced cross sections on radioactive targets remains a top priority for the SBSS program. Thus, it was concluded that there is a serious need to consider the feasibility of housing an intense neutron source on site at RIA.

SBSS working group speakers and discussion titles:

Stephen Becker (LANL), “SBSS R\&D Overview” (Plenary Speaker)
Stephanie Frankle (LANL), “Present status of nuclear cross sections and possibilities with RIA”
Robert Haight (LANL), “Nuclear level densities for SBSS”
Matthew Devlin (LANL), “Gamma-ray measurements for applications at RIA”
Gerry Hale (LANL), “Needs for the thermonuclear theory program”
Lee Bernstein (LLNL), “Reaction cross sections for isomers and radiochemistry”
John Ullmann (LANL), “Neutron capture measurements on radioactive targets”

SBSS Round Table:

Anna Hayes (Chair), Stephanie Frankle, Robert Little, Johndale Solem, Mike MacInnes, Jerry Wilhelmy, Thurman Talley, Gerry Hale, Robert Haight, John Ullmann, Steve Wender, Darrell Drake, Stephen Becker, Matthew Devlin, Lee Bernstein, Dennis Slaughter, Mark Stoyer, Andre Michaudon, Ben Gibson, and Ron Nelson.

IV. Accelerator Transmutation of Waste (ATW) Research Issues that May be Addressed at RIA

Conveners: Mark Chadwick (LANL) and Phillip Finck (ANL)

Working Group Participants: (to be listed)

Abstract:

ATW technology aims to transmute, through fast (10 keV - 20 MeV) neutron-induced fission and radiative capture reactions, long-lived radioactive species into shorter-lived species with half-lives typically less than 300 years. RIA could be used to collect pure mass-separated samples of selected actinide and fission product species and produce radioactive targets for the measurement of the important fission and capture cross sections at a neutron facility. Fission probabilities could also be measured in inverse kinematics (d,pf) or similar stripping reactions which mimic (n,f) reactions (at least at neutron equivalent energies above ~0.5 MeV). Other studies, such as those recently performed at GSI, involving the measurement of spallation and fission product distributions following A+p inverse kinematic reactions have been instrumental in testing and improving intranuclear cascade and pre-equilibrium models used in ATW calculations. Additional measurements of this type would be extremely valuable in further improving these models.

Highlight - two interesting possibilities:

a. RIA could provide beams of isotopes of materials important in ATW, such as actinides and fission products, which could be used for fabrication of isotopically pure targets. These could then be used for neutron-induced measurements of fission, radiative capture, etc. at a neutron source (either at RIA or elsewhere).

b. Fission cross sections play an important role in ATW. Fission probabilities could be measured in inverse kinematics using (d,p) or (t,p) stripping reactions to insert a neutron(s) into a target nucleus and cause fission, mimicking the (n,f) reaction. Such experiments have been successfully performed at Los Alamos in normal kinematics, but access to isotopically separated actinide beams at RIA would vastly expand the current database.

Introduction

Many countries including the US, Europe, and Japan, are pursuing accelerator-transmutation of waste (ATW) technologies to supplement plans for geological storage of radioactive waste. ATW technology aims to transmute, through fission and radiative capture, long-lived radioactive nuclides into shorter-lived nuclides with half-lives typically less than 300 years. The accelerator would bombard 1-GeV protons on a spallation target, producing a neutron source to drive a sub-critical reactor, or "transmuter", that would burn the waste. The sub-criticality of the transmuter provides extra safety and flexibility features over conventional reactor technologies. The systems under consideration generally operate at fast neutron energies (typically 10 keV - 20 MeV) rather than at thermal energies, in order to enhance the amount of fission relative to capture (so as not to build up higher levels of actinide species).

Such ATW technology requires accurate simulation computer codes to predict neutron spallation, and criticality in the transmuter. Accurate nuclear cross sections are needed in order to optimize the design, and to fully address safety considerations. Projects have been initiated in both nuclear theory and modeling, and experiments, to improve the cross section databases used by the ATW design codes. To date, nuclear data cross section measurements have not been supported in the US by the ATW program, though relevant measurements have been supported by the US Accelerator-Production of Tritium program. In Europe considerable experimental work has begun on ATW cross section measurements at CERN, Louvain-la-Neuve, Uppsala, and other laboratories. In the detailed summary below we explore how a RIA facility could also measure cross sections needed for ATW.

Detailed summary of ATW RIA session

Accelerator Transmutation of Waste (ATW) technology is being pursued by the US as a solution to long-lived radioactive waste problems, augmenting a geological repository. The current program envisions transmuting long-lived actinides (plutonium and higher minor actinides), together with certain fission products (Tc, I, ...), in a sub-critical transmuter driven by neutrons generated from ~1 GeV protons incident on a spallation target. To design and optimize such ATW systems, radiation transport simulation codes need accurate nuclear cross section data. There are two specific areas that must be considered for the transmuter and for the spallation target: (1) neutron cross sections at fast neutron energies (typically 10's of keV - 10's of MeV) for fission and capture, on actinides and fission products; (2) spallation and fission cross sections, including distributions of the residue nuclei, for incident protons and neutrons up to a GeV. Certain of these cross sections could benefit from a measurement program at RIA.

The time schedule for construction of a RIA facility (say 8 years) matches well with ATW needs. The ATW program plans a 10 year research period after which a subcritical test facility would be constructed (a full ATW prototype would not be built for many years after this). However, for the first three years of operation, conventional fuels would be used, and only after this period would ATW fuel be introduced and studied. Thus, accurate cross section data is needed for facility design prior to 2010-2013.

Certain top level ATW cross section data goals, with estimated uncertainties, have been provided by the ATW design engineers. They are as follows: (1) neutron production in proton spallation, important for neutron economy studies (20% accuracy); (2) isotope distributions of spallation/fission products, important for waste and corrosion studies (10-50%); (3) gas production and damage rates, important for systems lifetime characterization (30-50%); (4) actinide cross sections, important or criticality safety and transmutation rates (3-5%); and (5) decay data, for safety studies (10%).

While this workshop explored specific areas where a RIA facility could advance our understanding of cross sections important in ATW, it is important to recognize that the match between ATW needs and RIA is not perfect. Many ATW needs would require a neutron source facility (either at RIA, or making use of existing facility, such as LANSCE, for example). Certain important cross sections can be measured elsewhere or have already been measured, though undoubtedly additional data are needed in certain key cases (see below). Most materials in the transmuter and spallation target are long-lived and do not need to take advantage of an experimental capability that is unique for measuring reactions on short-lived nuclides. Finally, the current US design uses a large amount of plutonium compared to minor actinides, so that well-known plutonium cross sections tend to dominate the neutronics. This helps to mitigate deficiencies in our knowledge of minor actinide cross sections.

Sensitivity studies using simulation codes (MCNPX and others) have been performed to estimate the impact of uncertainties in actinide cross sections on key ATW transmuter parameters, such as the criticality (k-effective). These studies help to point to areas where improved cross sections are needed. Because of the importance of plutonium isotopes in ATW, the cross sections for these isotopes tend to be of crucial importance. An example where the current evaluated database appears to need improvement is ^{242}Pu. Another example of a minor actinide that needs improved fission measurements is ^{242}Cm, which builds up during the operation of ATW. RIA could provide high-purity beams of minor actinides and fission products. If a radioactive target fabrication capability existed, samples of high-purity actinide and fission product materials could then be used in subsequent neutron-induced experiments to measure fission and capture (either at a neutron source at RIA, or transported to another neutron facility).

Another interesting way to measure fission cross sections, relevant to RIA, is to use particle stripping reactions, e.g. (d,p), in inverse kinematics to insert a neutron into a nucleus and estimate fission probabilities. This method was pioneered in normal kinematics at Los Alamos by Britt, Wilhelmy, and Gavron. At RIA, one would use a beam of the actinide of interest incident on deuterons and tag the secondary proton events in coincidence with fission. This therefore avoids the need for a subsequent neutron-induced experiment. The drawback to this method is that conversion of results to an equivalent (n,f) cross section is somewhat model-dependent with the procedure becoming less reliable at low energies of ~1 MeV. However, the method does allow fission barrier information to be studied at energies below the neutron separation energy.

The Workshop also considered the use of Accelerator Mass Spectrometry (AMS) to measure cross sections when small samples have been irradiated in, say, neutron fission or capture reactions. The current AMS capability at ATLAS is likely to be available also at RIA. This method could be valuable when combined with methods used to fabricate small targets of high-purity isotopes at RIA.

Certain integral experiments would also be of interest to ATW, where ATW actinide fuel isotopes are irradiated in a neutron spectrum that replicates the fast neutron spectrum in the ATW transmuter, to study burn-up processes. Neutrons produced at RIA could be custom-moderated to replicate this spectrum, though this could also be done elsewhere at other neutron facilities. Again, high-purity actinide targets fabricated at RIA would be useful.

RIA could also investigate the physics of spallation and fission product distributions by studying p+A reactions in inverse kinematics, where A represents materials that may be used in the spallation target (e.g. Pb, Bi, U, W, …) and actinides. Here, the heavy fragments are kinematically “focused” at forward angles and the fragment distributions in Z and A can be measured. This field has recently been revolutionized by experiments at GSI where such reactions have been studied on a select number of nuclides at ~500 MeV/u. These experiments have already been instrumental in testing and improving the intranuclear cascade and pre-equilibrium models. Additional data at a range of energies below those studied at GSI, and for additional actinide and sub-actinide beam projectiles, would provide important data for ATW. Such data can also be used to test and improve new theories of nuclear fission that explore the multi-dimensional fission decay landscape more thoroughly to predict fission decay modes. It was noted, though, that a capability to post-accelerate ions with masses up to A=240 would have to be incorporated into the RIA design.

Finally, RIA measurements in inverse kinematics on proton targets could indirectly support ATW cross section work by guiding nuclear model development. While most cross sections needed for transmuter design are neutron-induced, proton-induced measurements do help probe the nuclear physics of level densities, gamma-ray strength functions, fission physics, etc. An ability to predict proton-induced measurements using our nuclear reaction cross section model codes will provide confidence in their reliability for neutron reaction predictions. Another area where RIA can support physics theory and model improvements is the optical model. New microscopic and phenomenological optical model theories aim to include the physics of elastic and inelastic scattering on a range of targets that have large variations in isospin. Testing such proton scattering predictions at RIA in inverse kinematics will improve these theories. These theories in turn provide reaction cross sections and scattering cross sections that are needed in ATW radiation transport simulations.

Working group speakers and discussion titles:
Phillip Finck (ANL), "ATW R & D Overview" (plenary talk)
Holly Trellue (LANL), "ATW simulations and the role of nuclear cross section data"
Stepan Mashnik (LAN), "RIA potential for improving models for ATW calculations"
Richard Pardo (ANL), "ATW production rates using accelerator-mass spectrometry"
Robert Haight (LANL), "Radiative capture measurements for ATW"
Steven Karataglidis (LANL), "Proton scattering at RIA & microscopic optical potentials"
Dennis Slaughter (LLNL), "RIA R & D for ATW"
Peter Moller (LANL), "Fission probability calculations for ATW"

V. Material Science and other Applications at RIA

(Condensed Matter, Space Radiation, Radiation Damage, Engineering, and Medical)

Conveners: Peggy McMahan (LBNL) and Dave Vieira (LANL)

Working Group Participants:
Peggy McMahan (LBNL), Pierre Bricault (TRIUMF), Gerald Morris (TRIUMF), Peter Fehsenfeld (Karlsruhe), Christine Eifrig (Karlsruhe), Janet Sisterson (Mass General Hospital), Ben Gibson (LANL), Tom Bowles (LANL), Jerry Nolen (ANL), Mike Nastasi (LANL), Al Zeller (MSU), Maria Petra (ANL), Dave Vieira (LANL)

Abstract:

The use of radioactive tracers implanted into materials was viewed as a developing and potentially powerful tool for the field of materials science and surface physics. In particular, radioactive beam implantation for wear and corrosion studies, beta-NMR studies of high T_c superconductors, semiconductors, magnetism, and perturbed angular correlation studies of materials were discussed. At RIA intensities, material modification studies using doping and annealing techniques could also be done. Other topics included space radiation effect studies with stable and radioactive beams, radioactive beam implantation for medical radiotherapy (see the biomedical applications section), neutron cross sections, neutron damage, and radiation effect studies with high-energy (20-400 MeV) neutrons produced as well as projectile fragmentation and the possibility of slowing these neutrons down to ultra-cold temperatures. The commercial use of radioactive beams appeared to be a limited, but viable option.

Introduction

This working group met for two sessions of the two-day RIA Applications Workshop. A range of informal talks and discussions on a variety of subjects were given and are listed in Table 1. Many diverse applications were considered. For each application we asked the following set of questions:

Is there an applicability to RIA?
Would the application be unique to RIA?
Would it fit into the expected running dynamics?
What resources would be needed?
What is the extent of the need? (How big is the community, etc.)
What is the long term outlook?
Is there a likelihood of outside support?

The applications considered used several facets of the versatile RIA facility include radioactive beams (both unaccelerated and post-accelerated), neutrons, and stable beams from the primary accelerator. Each application is discussed in more detail below.

It was recognized that there were several operational modes are possible for doing applications at RIA. The first mode, as one of the 2-3 shared users of the facility at a given time, would naturally have the largest impact on the nuclear science program. The second mode would be running on line but parasitically, for example in using high-energy neutrons behind the Li fragmentation target, or possibly use of recoil-separated fragment beams which are not stopped in the gas catcher. A third mode would work when long-lived radioactive isotopes are needed which are made in the ISOL targets during nuclear physics runs. These isotopes could later be tuned out of the source and either implanted directly or post-accelerated and then implanted. An example of this might be the use of ^{22}Na ($t_{1/2}$ = 2.3 yrs) for wear studies of artificial joints in prosthetics. A fourth mode, which is discussed at length in some of the other working groups, would be in mining via radiochemical and/or offline mass separation the "garbage" beam dumps for long-lived radioactive isotopes for selected applications.

The applications we considered fell into using four different "end-stations" at RIA. These are:

a. a radioactive beam implantation area using unaccelerated beams (100 eV - 100 keV) in Area 3 on Figure 1 [abbreviated as UAIS]
b. a low energy RIB implantation area (1-5 MeV) in Area 2 on Figure 1 [LEIS]
c. parasitic fragment-separated beams (up to 400 MeV/u) [FPES]
d. Fast neutrons (20-400 MeV) [HENS]

In addition, there was discussion on two other potential uses of RIA for which we did not have the experts present, but which we thought warranted further investigation. One is the possibility of using ultracold neutrons and low-energy neutrons at RIA. Neutron scattering at energies not being provided at the Spallation Neutron Source (SNS) facility may have importance for some biological applications and there may be other applications for which the SNS is not well suited. We did not have specific applications in this area but thought it should be investigated further. The other possibility is the production of a muon beam off of the Li target for muon-spin resonance studies.

Another topic of discussion was the interaction with industries that would like to purchase beam time at RIA. From the experience of those present, it was clear that it is difficult to get money up front to build an irradiation station. In most cases, one has to provide the facility and then basically market it to the industry. Once they are convinced that it is important and relatively painless to carry out experiments, then they will commit to paying for beam time. This means that: a) DOE has to commit to doing some applied work at the facility and may have to appropriate money for whatever add-ons to RIA are needed to make applications available; and b) there has to be someone at RIA who is a champion of these applications and who devotes the effort to learn enough about the industry to communicate with interested companies.

The bottom line of our discussion was that none of the applications which we discussed in this section were totally unique to RIA, although some would be unique in the United States. However, there is enough overlap between many of these applications that putting them all together, there may be enough potential to justify building a beam area. Two priority items would cover several items on this list of applications and provide a high degree of flexibility to RIA applications. These are:

1) Development of a low-energy irradiation/implantation facility in Area 2 (<1.5 MeV/u). This would include space for a radioactive beam implantation station for wear testing, corrosion studies, radioisotopes for radiotherapy applications,

perturbed angular correlation studies in materials, and other unforeseen applications.

2) Development of the high-energy neutron station as a parasitic area behind the primary fragmentation target. This would serve a variety of needs (high-energy time-of-flight cross section measurements, neutron damage studies, and a possible source for ultra-cold neutrons). Although not totally unique as WNR at LANL has similar capabilities, it was generally acknowledged that there were not enough neutron beams available in the world to meet existing needs.

We would like to see enough flexibility left in the design of RIA to possibly add other areas for applied work at some future time, in particular a beta-NMR beam line which might also be used as an ion implantation station for low-energy (100 eV-100 keV) radioactive beams. The other applications discussed, which would involve using an endstation off the fragment separator for high-energy beams, would be the lowest priority, as it would be the hardest to implement, and most of the need could be satisfied at other facilities.

Detail Discussion of Applications

1. β-NMR

Beta-detected nuclear magnetic resonance (β-NMR) is a tool for investigating thin structures and dilute impurities in condensed matter physics. Areas of application include many of the most interesting problems in the field, including high Tc superconductors, magnetic multilayers and semiconductor quantum wells. The principles for β-NMR and muon spin resonance (μSR) are almost identical: the time evolution of the spin polarization is picked up through anisotropic decay of a radioactive species, and the two methods provide complementary information. Thus far μSR is more developed because the intensities of polarized beams of low-energy radioactive nuclei have thus far been not available. This has changed with the advent of high-intensity radioactive beams from ISAC at TRIUMF and from ISOLDE.

β-NMR at RIA would not be unique since it can already be done at the facilities mentioned above. However, this is a new field with a growing community and there is room for a facility in the United States. A β-NMR facility at RIA would require a permanent set up in Area 3, using unaccelerated beams from either the ISOL or gas catcher targets, after the buncher. A footprint of about 30 m^2 would be necessary to install a polarizer and high-voltage platform. Experiments would require direct use of beams of light radioactive ions with half-lives from 10's of milliseconds to 10 seconds and intensities of 10^8/sec focussed into a small spot. Some examples of potential ions would be ^{8}Li, ^{11}Be, ^{15}O and ^{17}Ne.

2. Perturbed Angular Correlation (PAC) Spectroscopy with Radioactive Probes

PAC spectroscopy using radioactive probes has many applications for exploring surfaces, defects in high T_c superconductors, magnetic multilayers, etc. There are many potential ions, which could be used for this. Some examples include ^{8}Li, ^{111}In and Hg isotopes. One potential application would be to study the structure of Pu as it changes phases.

PAC spectroscopy at RIA would also not be unique since it can be done at ISOLDE or ISAC. The projects anticipated would be small studies. However, if there were an implantation station set up for other applications in either Areas 2 or 3, it could easily be used for PAC studies as well.

3. Wear, Corrosion and Kinematics Testing

Wear testing using radioactive probes is very important in the automobile industry. It also has economically important applications in the medical field in the development of better prosthetics, since at present 50% of hip and knee joint-replacement surgeries are to replace failing prosthetics. At the present time, irradiations for these tests for most of the world are being done at the cyclotron at the Research Center Karlsruhe. If anything is being done in the U.S. it is on a very small scale.

RIA would have an advantage in this field because of the high intensity near-stability radioactive beams it could generate. ^{7}Be and ^{22}Na are the ions of choice for the prosthetics work, and are needed in high purity (95-98%). These ions are long-lived and could be made elsewhere. However, if they could be made in the target parasitically, reionized offline and implanted in the low energy implantation station, then these studies might be done at RIA with little additional resources. There is extensive and growing need for these irradiations (in the prosthetics field alone, it is estimated that 500 parts/yr might be needed).

4. Radioactive Implantations for Medical Therapy: Stents, Wires and Seeds

The cover article of Physics Today in April 2000 discussed the use of radionuclides in therapy. Their examples included the use of beta emitters in the angioplasty procedure to prevent restenosis, or the collapsing of the artery after surgery. They also discussed brachiotherapy, the introduction of radioisotopes - beta, gamma or alpha emitters - directly into the tumor in the form of wires or seeds. This is a field on the verge of rapid growth. Making implants of some of these isotopes in the low energy implantation station for research purposes could potentially have major impact on the field. This topic was also addressed by the working group on medical applications.

5. Neutron Damage Studies

RIA will have a high energy neutron beam available parasitically whenever the liquid-Li fragmentation target is used. The use of this beam for bulk neutron damage studies will be very easily accomplished, and little is measured above 14 MeV at present. One application of such a beam is to develop new magnet materials for future high-energy accelerators like the muon-collider or a future upgrade of RIA.

RIA is not unique for these studies as they could be done at the WNR facility at LANL. However, RIA would be particularly convenient for the study of damage to superconducting magnet material because of the accessibility to cryogenic facilities. This testing would be associated with new projects in high-energy and nuclear physics and might generate some outside money. The scope of this would be occasional short runs over a long term.

6. Neutron Cross Section Measurements

The high energy neutron beams could also be used to measure neutron cross sections, either with the full neutron beam, or at lower intensities, using a longer flight path and TOF to determine the neutron energy. This capability already exists at the WNR at LANL but could also be incorporated here with minimal additional effort.

7. Space Applications

The energy of the primary accelerator is near the peak of the cosmic ray spectrum for heavy ions, and thus would be ideal for measurements of the radiation effects on both microelectronics and human cells, as well as calibrations for space science instruments. However, it appears problematic to implement this capability in a parasitic mode, which is probably the only way to be economically feasible. One would have to set up a Fragmentation Product End Station to take high energy fragments from the mass separator which are not needed by the main experiment. Radiation effects studies aren't sensitive to what the ion is but needs a range of masses in order to get a good range of LET (linear energy transfer). It seems unlikely that the design of the mass separator could allow transmission of a wide enough range of masses to make parasitic operation feasible without compromising the resolution of the separator for its main purpose. In addition, NASA is presently planning to build a facility for radiation effects testing at BNL around 750 MeV/u which would alleviate a lot of the need for a high energy facility in the United States.

Radiation effects also need to be measured with neutron beams, in particular for applications in the upper atmosphere and at the ground level. The high energy neutron facility with TOF would be ideal for these measurements.

Working group speakers and discussion titles:

Peter Fehsenfeld (Karlsruhe), “Application of RIA for High Sensitivity Wear Diagnostic Studies in Medicine and Industry” (plenary talk)
Gerald Morris (TRIUMF), “TRIUMF Beta-NMR Materials Science Studies”
Peggy McMahan (LBNL), “Radiation Effects Testing at RIA”
Janet Sisterson (Mass. Gen. Hospital), “Measuring Proton and Neutron Production Cross Sections needed for Cosmic Ray Studies”
Al Zeller (MSU), “Neutron Damage Studies needed for Magnets for Future High-Intensity Accelerators”
Jerry Nolen (ANL), “Production of Neutrons and Ultracold Neutrons at RIA”
Mike Nastasi (LANL), “Radioactive probes for Pu Studies; Radioactive Beam Implantation for Angioplasty”

VI. Facility Needs for Applied Research at RIA

Although some of the applied research discussed here would utilize the primary post-accelerated, high-intensity RIA beam, many experiments could be run as a secondary (or parasitic) user. In particular, flexibility should be built into RIA to utilize multiple targets, beam switching/sharing, and broad-range mass separation or pre-separation/post-separation fragment separator ideas to feed multiple users. Although the community was concerned about facility creep, many of these ideas are relatively simple and cost efficient if implemented up front. If sufficient room and flexibility is designed into the target and initial mass separation/recoil selection regions, other more involved ideas could be implemented as future enhancements. Increasing beam usage and flexibility is the key.

Two major recommendations from this community are: (1) including the capability to collect mass-separated/recoil-separated radioactive samples for the production of long-lived ($t_{1/2}$ > 2-5 day) radioactive targets and (2) building a high-intensity area to utilize the stable beam of the primary accelerator for radioisotope production via (HI,xn) reactions and for stable beam + radioactive target experiments. Additional RF power maybe required in the early stable beam acceleration stages to fully utilize this latter capability.

For the "bucket collection" of mass-separated (or recoil-separated) radioactive species as requested by several working groups, a broad range mass separator is envisioned with a movable electrostatic deflector system to peel off the desired species for collection. As many of species of interest lie close to stability and have relatively large production cross sections, high yields can be expected for those species that are efficiently ionized in the ion source. For fast recoil separation, species transmitted to the focal plane/degrader region of the fragment separator could be collected in separate pockets while allowing the primary beam to pass through to the gas stopper. More generally, a low-dispersion A/Q pre-separator (or possibly separate beam channels after the first dipole of the full fragment separator) could be used to separate exotic beams from the near stability beams which after further separation could be energy degraded and collected. These ideas build on the idea of utilizing more of the radioactive species that are being produced/released in the target to feed multiple users. An alternative approach is to employ multiple targets each with their own separator. In this spirit, a general purpose fragment separator for handling high-intensity, close-to-stability radioactive beams, which are not post-accelerated, is desired. This is likely to be of high utility to the nuclear physics community as well.

Naturally, RIA will need to have an infrastructure in place to handle highly radioactive materials (i.e. hot cells, radioactive fume hood, remote handling capability). These capabilities are also need for both the "bucket collection" of selected radioactive species and the high-intensity stable beam + radioactive target area mentioned above. Building in these capabilities for RIA from the outset is essential.

Finally, the idea of producing neutrons via projectile fragmentation or spallation neutrons via light ions on heavy targets was discussed. The projectile fragmentation neutrons appear to be quite unique in that the peak of the neutron energy distribution can be "tuned" by adjusting the energy of the primary beam and by the fact the high-energy neutrons are highly directional (e.g., calculations with 400 MeV/u U on Li yields a 200-400 MeV neutron beam with a 6 degree opening angle). By pre-bunching the beam at 1 MHz, time-of-flight experiments over a flight path of 100 m could be undertaken. By placing a sweeper magnetic directly downstream of the production target good access to this high-energy neutron beam would be possible for a variety of applied studies. Moreover, the directional nature of the projectile neutrons may be efficiently utilized for the production of ultra-cold neutrons (UCNs) where geometric limitations and thermal heating of the ultracold deuterium surface needed to produce UCNs is limiting. Low-energy neutrons may be obtained by moderating the high-energy neutron spectrum, however, we felt that RIA should not compete with existing or planned neutron spallation sources.

Given the high interest of the SBSS and ATW working groups as well as the nuclear astrophysics community in neutron reactions on radioactive targets, the possibility of siting a standalone neutron generator, possibly of the d+d or d+t type, was discussed. Although fairly mono-energetic and tunable neutron beams covering the 1 to 20 MeV region could be produced in a d+d accelerator, useful intensities are fairly low (10^8 n/sec into a cross section area of 1 cm^2). d+t neutron generators can provide higher neutron intensities (up to 6 x 10^{12} n/sec into 4π), but there emission is not so directional and the neutron energy is fixed at 14 MeV. Further thought is required to develop the best on-site neutron option for RIA.

VII. Program Advisory Committee

Anna Hayes (Los Alamos National Laboratory)
Jerry Nolen (Argonne National Laboratory)
Paul Schmor (TRIUMF, Vancouver, Canada)
Dennis Slaughter (Lawrence Livermore National Laboratory)
David Vieira (Los Alamos National Laboratory)

VIII. Local Organizing Committee

Tom Bowles
Mark Chadwick
Matthew Devlin
Robert Haight
Anna Hayes (co-chair)
Ben Gibson
Steven Karataglidis (scientific secretary)
Robin Shaw (conference secretary)
Dennis Phillips
David Vieira (chair)
Jerry Wilhelmy

IX. Acknowledgement

The Chair and Co-Chair would like to thank all of the workshop participants, speakers, discussion leaders, and session chairs for their active participation and the free exchange of ideas which made this workshop such a success. Special thanks are given to the working group conveners, the program advisor committee, and the local organizing committee for all of their hard work in organizing this workshop on short notice (less than 3 months). We gratefully acknowledge the outstanding day-to-day efforts of the conference secretary, Robin Shaw, who made all of the arrangements for the workshop, and Steven Karataglidis, the scientific secretary and workshop webmaster. We also thank Matt Devlin and Steven Karataglidis in preparing and downloading the workshop proceedings now on the workshop web page and to be preserved on a CD. Finally, we thank John McClelland in the Nuclear and Particle Physics (NPP) program office for his strong support and encouragement in hosting this workshop and to the Chemistry (C), Physics (P), and Theory (T) Divisions at Los Alamos National Laboratory for financial support.

Workshop Program

Sunday, October 29

6:00 pm to 9:00 pm: Reception at the Los Alamos Inn

Monday, October 30

Morning Plenary Session, Pinon Conference Room

8:30 to 9:00:	Registration
9:00 to 9:15:	Welcome and opening remarks, *David Vieira and John McClelland, LANL*
9:15 to 9:45:	Overview of RIA, *Jerry Nolen, ANL*
9:45 to 10:15:	ATW R & D overview, *Phillip Finck, ANL*
10:15 to 10:45:	Coffee Break
10:45 to 11:15:	SBSS R & D overview, *Steve Becker, LANL*
11:15 to 11:45:	Radioisotope and biomedical applications of RIA, *Jose Alonso, LBNL*
11:45 to 12:15:	Application of RIA for high sensitivity wear diagnostic studies in medicine and industry, *Peter Fehsenfeld, Karlsruhe*

Afternoon Parallel Sessions, individual working groups

1:30 to 3:15: Working groups, Session I

SBSS, *Johndale Solem, LANL, chair*

1. Present status of nuclear cross sections and possibilities with RIA, *Stephanie Frankle, LANL*
2. Nuclear level densities for SBSS, *Robert Haight, LANL*
3. Gamma-ray measurements for applications at RIA, *Matthew Devlin, LANL*
4. Needs for the thermonuclear theory program, *Gerry Hale, LANL*

Medical applications and radioisotopes, *Dennis Phillips, LANL, chair*

1. Introductory remarks, *Dennis Phillips, LANL*
2. Overview of possibilities for medical and industrial isotope production at RIA, *Jerry Nolen, ANL*
   Q & A regarding production rates
3. Radioisotopes for biosciences, *Tom Ruth, TRIUMF*
4. Heavy nuclides for nuclear medicine, *Robert Atcher, LANL*
   Q & A regarding heavy nuclides

Materials Science, *Peggy McMahan, LBNL, chair*

1. Beta-NMR materials science studies, *Gerry Morris, TRIUMF*
2. Radiation effects studies using stable and radioactive beams, *Peggy McMahan, LBNL*
3. Production of neutrons and ultra-cold neutrons at RIA, *Jerry Nolen, ANL*

3:15 to 3:45: Coffee break

3:45 to 5:30: Working groups, Session II

SBSS, *Steve Wender, LANL, chair*

5. Reaction cross sections for isomers and radiochemistry, *Lee Bernstein, LLNL*
6. Neutron capture measurements on radioactive targets, *John Ullmann, LANL*
7. Stockpile stewardship, radiochemistry, and radioactive beams, *Mark Stoyer, LLNL*
1. (ATW) RIA potential for improved models for ATW calculations, *Stepan Mashnik, LANL*

Medical applications and radioisotopes, *Dennis Phillips, LANL, chair*

1. Medical Applications of the South African National Accelerator Centre: Radioisotope production and particle beam therapy, *Meiring Nortier, NAC and Werner Richter, University of Stellenbosch*
   Q & A regarding NAC
2. Round Table discussion

Materials Science

Round table discussion on materials science using RIA

7:30 - : No host dinner at Gabriel's Restaurant

Tuesday, October 31

Morning Parallel Sessions

9:00 to 10:15: Working groups, Session III

ATW, *Mark Chadwick, LANL, chair*

2. ATW simulations and the role of nuclear cross section data, *Holly Trellue, LANL*
3. ATW production rates using accelerator-mass spectrometry, *Richard Pardo, ANL*
4. Radiative capture measurements for ATW, *Robert Haight, LANL*
5. Proton scattering at RIA and microscopic optical potentials, *Steven Karataglidis, LANL*

SBSS, *Anna Hayes, LANL, Chair*

Round Table discussion on SBSS

Medical applications and radioisotopes, *Dennis Phillips, LANL, Chair*

Round Table discussion / formulate summary

Materials Science, *Peggy McMahan, LBNL. Chair*

Round table discussion

10:15 to 10:45: Coffee Break

10:45 to 12:15: Working groups, Session IV

ATW, *Mark Chadwick, LANL, chair*

6. RIA R & D for ATW, *Dennis Slaughter, LLNL*
7. Fission probability calculations for ATW, *Peter Moller, LANL*

SBSS, *Anna Hayes, LANL, Chair*

Round table (cont.)

8. The role of nuclear physics in the Stockpile Stewardship Program, *Stephen Sterbenz, LANL*

Medical applications and radioisotopes, *Dennis Phillips, LANL, Chair*

Round table discussion / write summary

Afternoon Plenary Session, Pinon Conference Room

1:30 to 3:30: Summaries by each Working Group

Medical Applications and Radioisotopes, *Dennis Phillips, LANL*
ATW, Mark Chadwick, LANL
SBSS, Anna Hayes, LANL
Materials Science, Peggy McMahan, LBNL

3:30 to 4:00: Closing remarks, *Dave Vieira and Dan Strottman, LANL*

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